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Energy and cost savings with continuous low temperature heating versus intermittent heating of an office building with district heating

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ABSTRACT

Future low-temperature district heating systems (LTDH) require supply and return temperatures as low as 55 °C and 25 °C, respectively. In this direction, the use of night setbacks in heating of office buildings is a problem. This article investigated in a typical office building with large distribution system by tests and simulations the energy and cost savings by changing the control of the heating system from a continuous high-temperature operation either to a high-temperature intermittent heating or to a continuous low-temperature operation. Both strategies secured thermal comfort and resulted in similar energy savings of approximately 11% in the specific building. The reduction of the return temperature was higher under continuous low-temperature operation, resulting in additional cost savings due to a motivation tariff for low-temperature operation used in Denmark. As a result continuous low-temperature operation can achieve the highest total cost reduction for heating of 23.1%. Even if the results refer to the specific building, continuous low-temperature heating may result in significant energy savings in other buildings with large distribution systems. Moreover, implementing motivation tariffs towards LTDH may provide additional economic incentives. Therefore, it is interesting to investigate continuous low-temperature heating in each building and quantify the cost and energy savings towards LTDH.

1. Introduction

1.1. Low-temperature district heating

According to the European Green Deal, the integration of renewables, energy efficiency, and other sustainable solutions across different sectors will allow attaining decarbonisation by 2050. District Heating (DH) can play an essential role in this direction by integrating renewable energy sources [1–3]. Current DH energy sources, like excess heat from fossil fuel-based power generation, oil or natural gas boilers, and excess fossil fuel-based industrial heat must be replaced by sustainable energy sources by 2050 [4]. To integrate DH in future smart energy systems and increase the efficiency of renewable energy sources such as geothermal heat, solar thermal heat, and large-scale heat pumps in DH networks, the temperatures in DH systems must be reduced to the level of Low-Temperature District Heating (LTDH). LTDH operates with supply and return temperatures as low as 55 °C and 25 °C, respectively [4–7]. Reducing the DH temperatures will also reduce the primary energy consumption and distribution heat loss [8–10].

Low-temperature operation of DH systems can only be achieved through the low-temperature operation of heating systems in buildings. The network operator controls the supply temperature and can reduce it in times of lower heat demand. However, when the supply temperature reaches a certain level, the return temperature limits the extent to which it is possible to lower the supply temperature. The end-user controls the return temperature. Therefore, DH network operators have a clear interest in helping consumers to lower the return temperature [11].

1.2. Problem description

To save energy, in many office buildings, heating systems are controlled with a night setback strategy or they are completely turned off during non-working hours. Night setbacks gradually

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reduce the indoor temperature and the heat loss in these buildings during non-working hours. Then, the buildings are reheated the next morning to increase the indoor temperature and secure the expected comfort [12]. The reheating process is performed quickly and requires high supply temperatures resulting in high return temperatures. As a result, the need for cost and energy reduction through temperature setback control strategies conflicts with the required future low-temperature operation of DH networks.

1.3. Motivation tariff for the low-temperature operation of heating systems

To promote the low-temperature operation of heating systems in Denmark, network operators have implemented a bonus or penalty for end-users in the form of a motivation tariff [13]. The bonus or penalty for the end-users is typically in Denmark 1% of the heating price per degree the flow weighted average return temperature is below or above a reference temperature. The flow weighted average return temperature on a yearly basis is typically measured by the electronic energy meter used for the billing of district heating [11,14].

1.4. State of the art

In an article by Neirotti et al. [15], the approach to replace night setback with continuous heating with low temperatures suitable for LTDH was investigated. According to the results, the continuous operation of the heating system allows a temperature reduction in the network from nominally 90 °C to 50–60 °C without causing thermal discomfort, but the energy demand for heating was increased by 3.5% compared to the night setback operation. However, the investigations did not assess the potential economic benefit due to the motivation tariff. Moreover, the reference study used average building features obtained from actual cases without detailed modelling of each building. As a result, some approximations were made due to some missing information. The reference article also recommended that a specific building simulation model would be needed to increase the reliability of the results, leading to a more complicated model with higher computational resources. This recommendation was taken into account in the actual work and therefore, this article provides new knowledge, especially on the energy savings due to the low-temperature operation of heating systems in buildings.

Pang et al. [16] investigated the energy savings due to temperature setbacks during unoccupied hours in US households. According to the results, only a few cases showed energy savings of over 30% regarding the HVAC systems. Gunay et al. [17] investigated the duration of the temperature setback periods of office space using EnergyPlus simulations. According to the results, a 30% reduction in heat could be achieved by increasing the weekday temperature setback periods. Liu et al. [18] investigated a dynamic control approach based on temperature and time to fulfil the heating demand for university buildings in a Chinese DH system. According to the operation data, the annual heat use can be reduced by 14.7%–28.7%. Deng et al. [19] investigated the use of thermostat setback and occupancy control in office buildings through EnergyPlus simulations and actual tests. According to the results, the energy consumption could be reduced by 30% with thermostat setback control. None of the previous studies compares the energy savings due to night setback with the energy and cost savings under continuous low-temperature heating as done in this article.

Considering the variations in energy savings presented in the previous articles, it can be concluded that night setback operation savings depend on the actual building. This has also been found in the following two articles. According to Gadd et al. [20], night setback can be better applied to buildings with high heat demands due to poor insulation and high infiltration rate. Zhang et al. [21] also indicated that night setback is a control strategy that is not suitable for low energy buildings concerning economic factors and energy efficiency.

Jangsten et al. [22] investigated the potential for reducing the operating temperatures in heating systems based on actual recorded data from 109 radiator systems in Swedish DH systems. According to the results, radiator systems can operate with supply temperatures below 55 °C for an outdoor temperature of 5 °C. However, the studies did not address the impact of the low-temperature operation of heating systems on the potential energy savings due to reduction in heat losses from the distribution system outside the heated rooms and increased efficiency.

As a result, the potential for energy savings due to intermittent heating varies based on the heat demand profile of the specific building. For buildings with relatively low-energy use, this potential may be limited. Continuous operation of the heating system with a minimum supply temperature results in low return temperatures but may also result in energy savings. However, there is a knowledge gap in evaluating the energy and cost savings due to continuous low-temperature operation compared to intermittent heating. Cost benefits for low return temperature due to a motivation tariff in LTDH systems is a new element that needs to be included in evaluating different control strategies for heating systems.

1.5. Aim and scope

The study aims to investigate the energy and cost savings in an office building by changing the control of the existing heating system from a continuous high-temperature operation either to a high-temperature operation with night setback or to a continuous low-temperature operation. The investigation is based on the test of the comfort performance of the proposed new control strategies in a cold period of the heating season and calculations of the yearly energy performance based on dynamic simulations.

The scope of this investigation was to compare night setback control and continuous heating with minimised supply temperature curves by simulating and testing the proposed strategies in a Danish office building. The energy and cost savings of the two different control strategies were evaluated based on the reduced annual energy use for heating and the additional economic benefit due to a typical motivation tariff for low-return temperature used by Danish district heating companies. This study investigated different control strategies at the building level. The technical and economic benefits of peak shaving concerning the entire DH network were not considered in this study.

1.6. Novelty

This study presents new knowledge because it compares the use of night setback with continuous low-temperature heating, based on cost savings due to the reduced energy for heating and the additional economic benefit due to motivation tariff for low return temperature in district heating systems.

2. Case study description

The building case selected was Building 118 of the Technical University of Denmark (DTU) campus in Kgs. Lyngby, Denmark. The building was constructed in 1970. The total area of the building is 5560 m^2, split into three heated floors of 1390 m^2 each, and a partially unheated basement of 1390 m^2. The two façades have north-northeast and south-southwest orientation. It consists of offices, meeting rooms, and corridors. The typical working hours in the building are from 9:00 to 17:00 on weekdays.

This specific building was selected because a night setback based on a weather compensation curve control strategy was initially used. However, due to complaints about insufficient temperatures, especially in the gable offices, this control strategy was abandoned and replaced by continuous heating. Later, the building was renovated with new low energy glazings. The selected building case is shown in Fig. 1.

The heat supply comes from a DH company that supplies heat to a central campus substation, from where it is distributed to all buildings by a local campus network. The space heating system in the actual building is a 1-string system split into a circuit for each façade. Building 118 is controlled by a building management system (BMS) monitored by the DTU Campus Service (CAS). The substation of Building 118 is illustrated in Fig. 2.

Hot water is distributed from the substation to each façade through a riser located at the façade. Each riser is connected to horizontal pipelines on each floor, which distribute hot water to different offices. The water in each distribution system returns to the substation by two risers located at the west and east ends of the building and pipes in the basement. All pipes are uninsulated as heat loss is used to heat the rooms.

The heating elements installed in each office were mainly finned tube convectors installed in a windowsill box. These convectors were initially designed as supplements to help reduce the cold downdraft from the windows, as the building was designed initially with air heating. The original U-value of the glazing units in the windows was 2.8 W/m^{2}K. The ventilation system did not recover heat and worked with an air change rate of 4 h^{-1}. However, the ventilation system has been inactive since 1973, and the glazing units were replaced with new ones with a U-value of approximately 1.3 W/m^{2}K. As a result, the heat demand became relatively lower owing to the reduced heat losses from the glazing units. Under these conditions, the finned tube convectors were sufficient to compensate for the lower heat demand. In some rooms on the ground floor, 2-panel radiators were installed. The finned tube convectors installed in most office rooms are shown in Fig. 3.

In all rooms, the indoor temperature was controlled by thermostats with remote sensors. By setting the thermostat to position “3″, the indoor temperature was set between 20 °C and 22 °C.

The initial weather compensation curve used during the night setback control strategy and maintained after this strategy was abandoned in Building 118 is shown in Fig. 4.

3. Methodology

The methodology used was to compare night setback and continuous heating in the building case through actual tests and building energy simulations. The purpose of the actual tests in the building case was to verify that each of the different strategies can secure the required thermal comfort in several selected critical office rooms. For this reason, indoor temperature loggers were installed in these rooms. In addition, the influence of each strategy on the supply and return temperatures was identified using data recorded by the BMS system during a limited test period.

Further, due to the limited testing period, building energy simulations were used to quantify the annual energy use for heating under the two different control strategies. A comparison of the simulation results regarding energy use can pinpoint the optimal strategy to achieve energy savings.

The two control strategies were evaluated based on the energy and relative cost savings according to the calculated annual energy use for heating. An additional economic benefit was part of the analysis, as in Denmark, it is common practice to have motivation tariffs to stimulate the end-users to operate their heating systems better. This study assumed a typical bonus of 1% in the end-users energy bills for each degree lower return temperature.

3.1. Control strategies

To compare night setback with continuous heating, it is essential to use a typical night setback strategy with a sufficient temperature reduction. Due to the high supply temperature used in the building case, under the night setback strategy, the supply temperature of the initial weather compensation curve was reduced by 20 °C from 18:00 to 6:00. After 6:00, the supply temperature was restored to the daytime setting. Different night setback control strategies, such as turning off the heating system during the whole weekend, were not investigated because they could not be implemented in the old BMS system and tested in the actual building case.

On the other hand, a minimum required supply temperature under continuous heating was calculated and used to secure a low-temperature operation and thermal comfort. For this reason, a new weather compensation curve was calculated based on heating degree day analysis, the annual energy use for heating recorded by the BMS system, and the capacity of the space heating system. Under continuous heating, the building was heated according to a weather compensation curve during both working and non-working hours. Two different weather compensation curves were used for this investigation: the initial weather compensation curve used in the heating system and presented in Fig. 4 and a new one based on the minimum supply temperature required. The new weather curve was also modified by shifting the curve up by 2 K. The calculation of the new weather compensation curve is presented in Section 3.2.

An overview of the control strategies tested and simulated with the IDA ICE model of the building case are presented in Table 1.

Fig. 1. Building 118 of the DTU campus at Kgs. Lyngby, Denmark.

Fig. 2. Substation of the building case.

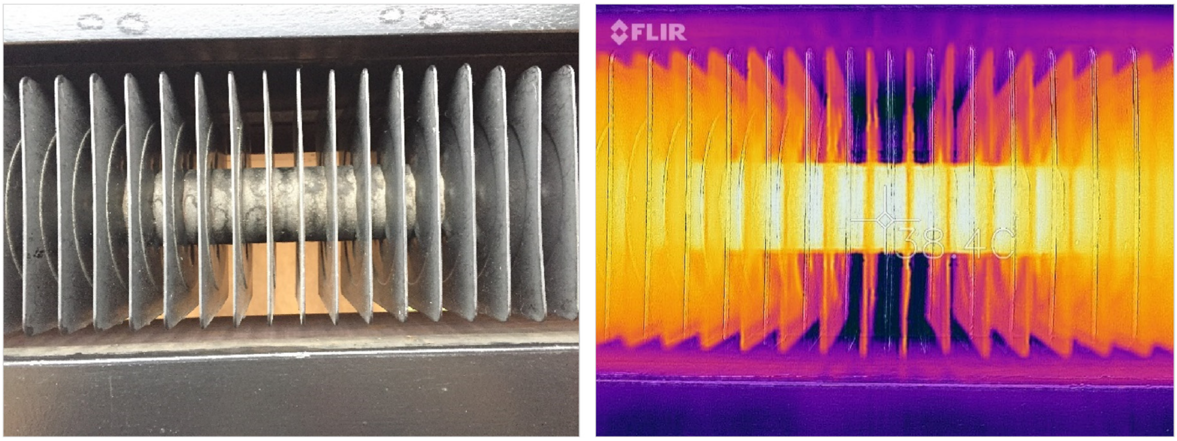

Fig. 3. The finned tube convector installed in a windowsill box is depicted with a normal and a thermographic photograph.

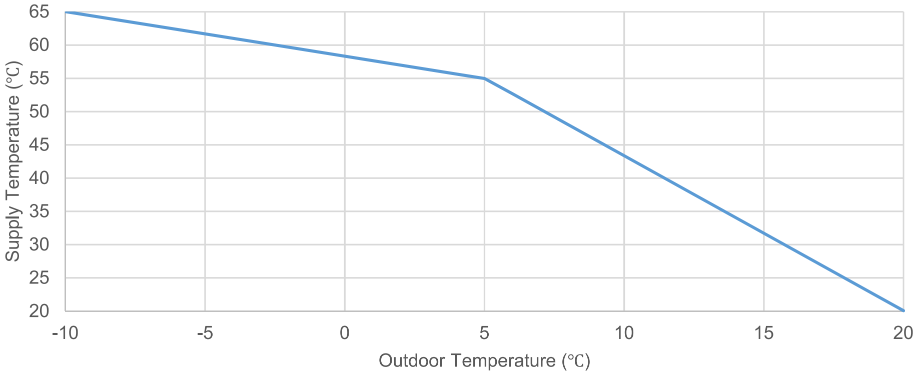

Fig. 4. Initial weather compensation curve used in the building case.

3.2. *Calculation of the minimum supply temperature*

In this section, the calculation of the minimum supply temperature required under continuous heating is performed, assuming a correct and uniform operation of the heating system. The minimum supply temperature required is expressed as a weather compensation curve that can be implemented directly in the BMS controller.

In one-string systems, a solution to achieve low-temperature operation is to reduce the supply temperature. Owing to the small cooling of the water, the return temperature follows the supply temperature variations. As a result, the return temperature can be minimised by minimising the supply temperature. However, if the supply temperature is lowered too much, insufficient heat will be supplied to the building.

To calculate the minimum supply temperature required in the building case in the form of a weather compensation curve, the following process was followed:

- The heating capacity of the heating system was identified, including both the heating capacity of each radiator and the heat loss of the uninsulated pipes of the distribution system inside the heated rooms.
- The heating demand coefficient of the building was found from the measured heat consumption for space heating for the heating season divided by the heating degree hours for the heating season
- The required cooling of water at different temperatures was estimated. This can be either a constant value or a value depending on the supply temperature.
- The minimum supply temperature for each outdoor temperature was calculated to form the weather compensation curve.

This overall calculation process is formulated by a mathematical equation as follows:

The heating capacity of each fined tube convector (P_{sq}) in $W/\,m$ was retrieved from the manufacturer datasheet at a reference temperature set. Like the one installed in the building, a square plate convector has a higher surface area than a finned tube convector, but the most representative data found was for a square plate convector. A higher surface area indicates a higher heating capacity. To approximate this difference in heating capacity, the ratio between the circumference of a square and a circle is as follows:

$$P_{circ} = P_{sq}\ \frac{4}{\pi} \tag{1}$$

A convector or radiator that is not completely free on three sides has a reduced heating capacity. According to SBI 175 [23], a factor of 0.9 must be applied to this specific installation of a convector.

$$P_{circ,adj} = P_{circ} \cdot 0.9 \tag{2}$$

Considering the length L of each module in m, the heating capacity of each convector (P_{module}) in W can be calculated as:

$$P_{module} = QP_{circ,adj} \cdot L \tag{3}$$

by taking the heating capacity per meter of convector and adjusting it for the windowsill placement.

Furthermore, there is an uninsulated pipe passing through each module that contributes to the maximum heating capacity of each module. Using the calculation tool “ROCKTEC” [24] based on the reference temperature selected, the pipe diameter, and a pipe emissivity factor of 0.9, corresponding to painted pipes, the heat loss (P_{pipe}) can be calculated.

As a result, the combined heating capacity in W of each module is:

$$P = P_{module} + P_{pipe} \tag{4}$$

The sum of the individual heating capacities of all identical modules should be calculated. Each of the three floors had 68 finned tube convectors (or equivalent panel radiators in a few refurbished meeting rooms). Thus, the total heating capacity (P_{tot}) in W of the building case is:

$$P = 68\ modules \cdot 3\ heated\ floors\ \cdot P \tag{5}$$

The next step in the calculation process is to calculate the heating demand coefficient of the building case. First, the Degree Day number of the day is calculated based on the Danish context [25,26], as the temperature difference ($\Delta T(T)$) between the internal daily average temperature of 17 °C used in Denmark and the external daily average temperature for one day at each outdoor temperature (T) between −12 °C and 12 °C:

$$\Delta T(T) = 17 -\ T \tag{6}$$

The Heating Degree Days ($HDD(T)$) for each outdoor temperature between −12 °C and 12 °C was calculated as follows:

$$HDD(T) = \Delta T(T) \bullet n_{days}(T) \tag{7}$$

where $n_{days}(T)$ is the number of days in which each outdoor temperature between −12 °C and 12 °C occurs. The Heating Degree Days ($HDD(T)$) measure the heat demand for space heating for each outdoor temperature −12 °C and 12 °C as the difference between the internal daily average temperature of 17 °C and the external daily average temperature [25,26].

The total Heating Degree Hours (HDH) of the year in $K \bullet h$ is calculated as the sum of the $HDD(T)$ for each outdoor temperature between −12 °C and 12 °C times the 24 h per day.

$$HDH = \sum_{-12\ ^\circ C}^{12\ ^\circ C} HDD(T)\ \bullet 24 \tag{8}$$

The heating demand coefficient for each outdoor temperature in kW/K is calculated as follows:

$$Heating\ demand\ coef = \frac{E}{HDH} \tag{9}$$

where E is the annual energy use in kWh obtained from the BMS of the building case.

The heat demand (in W) for each outdoor temperature ($P(T)$) between −12 °C and 12 °C was calculated as follows:

$$P(T) = Heating\ demand\ coef \bullet \Delta T(T) \tag{10}$$

To calculate the minimum supply temperature for each outdoor temperature, the Logarithmic Mean Temperature Difference ($LMTD(T)$) between the radiator temperature and the indoor temperature at each outdoor temperature that determines the heat output (in W) from the radiator, was calculated as follows:

Table 1
Overview of the different control strategies tested and evaluated under dynamic simulations through IDA ICE.

Control strategies	
Reference	Continuous heating – Initial weather compensation curve
Alternative 1	Night setback – Initial weather compensation curve with 20 °C offset from 18:00 to 6:00
Alternative 2a	Continuous heating – New weather compensation curve
Alternative 2b	Continuous heating – Modified new weather compensation curve

$$\frac{P(T)}{P_{tot}} = \left(\frac{LMTD(T)}{LMTD_0}\right)^n \tag{11}$$

where $LMTD_0$ is the logarithmic mean temperature difference at the reference temperature set. The exponent n has a value related to the convector. The general equation for calculating the $LMTD$ is:

$$LMTD = \frac{T_{sup} - T_{ret}}{\ln\left(\frac{T_{sup} - T_{in}}{T_{ret} - T_{in}}\right)} \tag{12}$$

where T_{sup} is the supply temperature, T_{ret} is the return temperature, and T_{in} is the indoor temperature. To calculate the cooling of the water in the heating system, for a 1-string convector-based system such as that in the building case, the cooling of the supply temperature is smaller than that of modern 2-string systems. From Eqs. (11) and (12), the supply temperature at each outdoor temperature between -12 °C and 12 °C was calculated.

3.3. Test of different strategies in the building case

Before testing the different control strategies in the actual building case, several indoor temperature loggers were placed in different typical offices on different floors. During the test of the different strategies, from the December 12, 2020 to the December 22, 2020, the loggers were used to monitor the indoor temperature as one of the parameters to evaluate the different control strategies.

The indoor temperature loggers used were of the type “HOBO U10″ made by ONSET [27]. Compared to a calibrated temperature sensor, the logger's reading showed an accuracy of ±0.5 °C, which suits the required precision of this project. The logged temperature is the dry-bulb air temperature. The loggers were set up to record the temperature every 15 min. The data from the loggers were extracted using the program “HOBOware".

Fig. 5. HOBO U10 temperature data logger.

Table 2
Position of HOBO loggers in different offices of the building case.

Room nr.	Room description	Room floor
002	South office – gable room	Ground floor
007	North meeting room	Ground floor
107	North office	1st floor
202	South office – gable room	2nd floor
207	North office	2nd floor
210	South office	2nd floor

The HOBO logger used for identifying the indoor temperature of the building is shown in Fig. 5. The positions of several HOBO loggers used in the building case are presented in Table 2. The position of the HOBO loggers was selected to identify the indoor temperature distribution in typical office rooms in the heated part of the building. All the HOBO loggers were placed in a sun-sheltered position inside the rooms, about 1.5 m above the floor.

Two gable rooms on the ground floor and 2nd floor were included because they are critical rooms in terms of comfort temperature. The reason is that these rooms have an additional external wall that results in higher heat losses than the rest of the office rooms.

During the test period, data from the BMS system were used to evaluate the supply and return temperatures recorded to identify the effect of each strategy on the operating temperatures of the heating system.

3.4. Building energy simulations

Because it was not possible to test the different control strategies during a whole year period, a model of the building case was created using the software IDA Indoor Climate and Energy (IDA ICE) by EQUA Simulation AB [28]. The purpose of the model was to perform dynamic simulations to estimate the annual energy use for heating under the different control strategies examined. The dynamic simulation of each control strategy for the whole year was performed under the Danish Reference Year (DRY) conditions from 2001 to 2010 used in Denmark [29].

A module of the building case was modelled in IDA ICE. The length was 3 m and the width was the same as the building case. The module included different room types. The width of the north rooms was 6.22 m, the width of the south rooms was 4.42 m, and the width of the corridors in between was 3.29 m. The height of the office rooms was 3 m, whereas the height of the corridor was 2.25 m due to a suspended ceiling. The suspended ceiling, however, was not included in the IDA model for simplicity. An illustration of the representative section of the building case modelled in the IDA ICE is illustrated in Fig. 6.

The modelling of the building envelope was based on the actual U-values of the external walls, roof, basement, new glazing elements, window frames, and actual window area, according to the schematic of the building as presented in Table 3.

The design and operation of the heating system are based on the actual operating conditions. In each office room, two heating elements were placed. One represented the convector, and the other represented the heat losses from the pipes. The heat output was defined based on the supply temperature and the indoor temperature setpoint. The convector was controlled based on a temperature setpoint for heating of 22 °C. A continuous heat loss based only on the supply temperature was modelled for the heating element representing the heat losses. No radiators were placed in the hallways. Radiators representing only heat loss were placed in the basement.

The lighting in all the areas was assumed to be 5 W/m^2. Regarding the heat gains from the equipment, a total value of 65 W was set in the office rooms and a total value of 538 W in the southern meeting room.

Finally, model validation was performed by comparing the simulation results for April and December of 2020. In April of 2020,

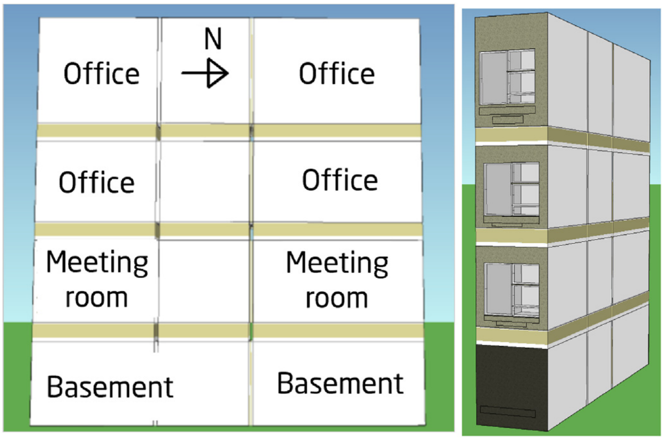

Fig. 6. Representative section of the building case modelled in IDA ICE.

Table 3
U-values of the building envelope used for building the IDA ICE model.

Part of the Building envelope	U-value (W/m^2 ·K)	g-value
Roof	0.20	
External wall	0.60	
Basement floor	3.35	
Window glazing (south)	1.1	0.62
Window glazing (north)	1.4	0.61
Window frame	2.2	

the building was occupied after the Covid-19 restrictions, but there were no temperature sensors installed at that time. In December of 2020, the temperature sensors were implemented, but there was no occupancy in the building due to new Covid-19 restrictions. The initial weather compensation curve from Fig. 4 was implemented in the building and model simulations during both periods. .

3.5. Economic benefits

The control strategies were also investigated from an economic perspective. The cost of DH energy in Denmark is based on a fixed part related to the investment cost and a variable part related to energy consumption. The fixed cost is marginal in comparison with the variable heating cost. Consequently, a lower annual heating consumption would result in a lower variable cost.

Regarding the bonus or penalty calculation due to the motivation tariff, the flow-weighted average return temperature is usually used as a direct output from the energy meters installed in substations in Denmark. As the model of the heating of the building did not include a model of the district heating network, we do not have data on the district heating flow and therefore, the return temperature of the heating system was averaged based on the energy use. It is assumed that the energy-weighted average return temperature can be used instead of the flow-weighted average return temperature.

The annual energy-weighted average return temperature was calculated according to Eq. (13). The hourly calculated energy use for heating (E_i) and the return temperature ($T_{ret,i}$) along with the energy use for heating (E_{tot}) were obtained from the IDA ICE simulation results for each control strategy.

$$\overline{T_{ret}} = \frac{\sum T_{ret,i} \cdot E_i}{E_{tot}} \tag{13}$$

The savings due to the motivation tariff were calculated as an additional 1% reduction in the overall cost of heating per degree reduction in the energy-weighted average return temperature. The reference for this comparison was the use of the initial weather curve for continuous heating.

4. Analysis and results

4.1. Calculation of the new weather compensation curve for continuous heating

The reference temperature set of 70/55/20 °C was used to calculate the building case's total heating capacity. Using the datasheet [30] from the company Spiral, a finned tube convector with a pipe diameter of 32 mm, a plate thickness of 2.5 mm, and a tube diameter of 92 mm will have a heating capacity of 320 W/m at the temperature set 70/55/20 °C. The length of each module is 2.8 m. As a result, from Eqs. (1)–(3), each module has a heating capacity of 1027 W. The heat loss from each uninsulated return pipe is calculated using the calculation “ROCKTEC” [31] with an assumed maximum return temperature of 55 °C, a pipe diameter of 33 mm, and a pipe length of 3.3 m. This results in a heat loss of 110 W for each module. The combined heating capacity of each module is therefore estimated to be 1137 W. Therefore, the total heating capacity of the building at 70/55/20 °C is the sum of the individual capacities of the 204 modules, which is 239 kW.

Based on data from the energy meter, a constant value of 3 K cooling was assumed for each outdoor temperature. T_{in} was equal to 22 °C, $T_{sup} - T_{ret}$ equal to 3 K, and T_{ret} equal to $T_{sup} - 3\ K$.

To calculate the heating demand coefficient, the available data regarding the energy use from November to February were used, representing a period in which the heating system was active under normal operation and occupancy. The total energy use of the examined period was 178 MWh, and the total HDD was 1771. According to Eq. (9), the heating demand coefficient is calculated to be 4.1 kW/K.

The new weather compensation curve for low-temperature continuous operation is calculated from Eqs. (10)–(12) and is illustrated in Fig. 7. Moreover, a comparison with the initial curve was used for the continuous operation of the heating system of the building case. At an outdoor temperature of 0 °C, the new weather curve results in a supply temperature of 44 °C, which is approximately 15 °C lower than that obtained with the initial curve.

4.2. Test results of different strategies in the building case with a focus on operating and indoor temperatures

The different control strategies were tested from December 12, 2020 to January 18, 2021. In this period, the office building was not in use due to Covid 19 restrictions. Therefore, there was no internal heat gain, making the test conditions more severe than if the building had been used. Before the test, it was secured that all thermostatic radiator valves were adjusted to a standard comfort setting of 3 equivalent to 20–22 °C.

Fig. 8 shows the indoor temperature recorded by the HOBO loggers in the different rooms during the test of the different control strategies from the December 12, 2020 to the December 22, 2020. More specifically, from 12th of December to the 15th of December, the night setback strategy with a 20 °C offset during weekdays from the initial weather compensation curve was tested. From the 15th of December to the 22nd of December, continuous heating under the initial weather compensation curve was tested. Finally, on the 19th of December, the new weather compensation curve for continuous heating was tested.

Based on the HOBO loggers' recordings, the test night setback of the night setback strategy with 20 °C offset during weekdays

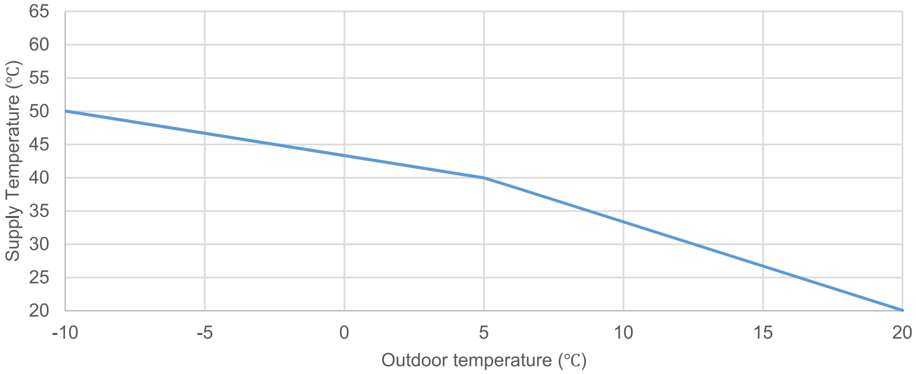

Fig. 7. New weather compensation curve for continuous heating under the minimum supply temperature required by the heating system.

resulted in a low indoor temperature during the morning of the next day, especially in the rooms on the second floor with higher heat losses owing to the roof (207 and 210) and gable room (202). The indoor temperature increased during the working hours to drop again during the night. The initial weather compensation curve test under continuous heating resulted in a constant and sufficient indoor temperature during working and non-working hours. A sufficient indoor temperature was considered 22 °C, but an indoor temperature at 21 °C was also acceptable. The new weather compensation curve test resulted in an acceptable indoor temperature in most rooms except for the gable rooms (002 and 202). In these two rooms, the indoor temperature was reduced by approximately 2 °C compared to that under the previous control strategies because of the additional head loss in these rooms. The low indoor temperature in room 007 could be explained by the incorrect placement of the temperature sensor of the thermostatic radiator valve. It was influenced by the heat flow from the radiators and therefore did not adjust the heat output based on the actual indoor temperature.

A possible solution to increase the indoor temperature in the gable rooms is to install additional local heaters to compensate for the higher heat loss. However, a more simple solution was investigated to secure thermal comfort by increasing the new weather compensation curve by 2 °C. The modified new weather compensation curve was tested in the building case from 6th to 18th of January of 2021, as illustrated in Fig. 9.

Fig. 9 shows that the indoor temperature in all the rooms is acceptable under the modified new weather curve. The peak values recorded on different days are due to solar gains. Room 107 represents 2/3 of the standard office rooms in the building case. In room 007, on the 13th of January, the misplaced thermostat sensor was set to position “5” to increase the heat output from the radiator.

Fig. 10 and Fig. 11 presents the space heating systems' recorded supply and return temperatures tested under the different control strategies. The results show a clear reduction in the return temperatures when lower supply temperatures are used. According to the results, the test of the night setback strategy resulted in return temperatures close to 50 °C during the working hours. The test of the initial weather compensation curve resulted in return temperatures higher than 40 °C. The test of the new weather compensation curves resulted in return temperatures close to 40 °C.

4.3. Simulation results of different control strategies with a focus on indoor temperatures and total energy consumption

In Fig. 12, the indoor temperature of a south and north offices on the second floor of the building are illustrated based on the IDA ICE simulations and the actual measurements on the 16th and 17th of December of 2020 to validate the IDA ICE model. In both cases, the

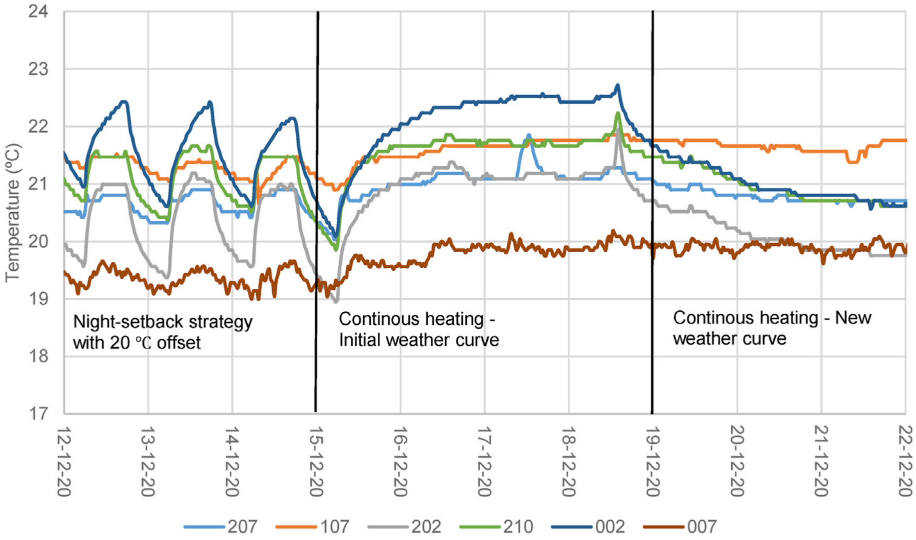

Fig. 8. Indoor temperature recordings by the HOBO loggers in different offices of the building case under the test of the different control strategies.

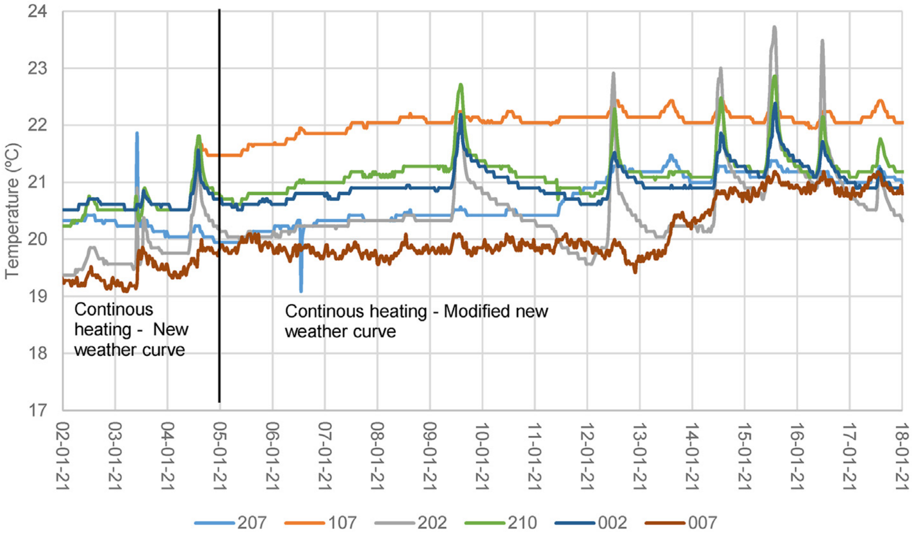

Fig. 9. Indoor temperature recordings by the HOBO loggers in different offices of the building case under the test of the modified new weather compensation curve by 2 °C.

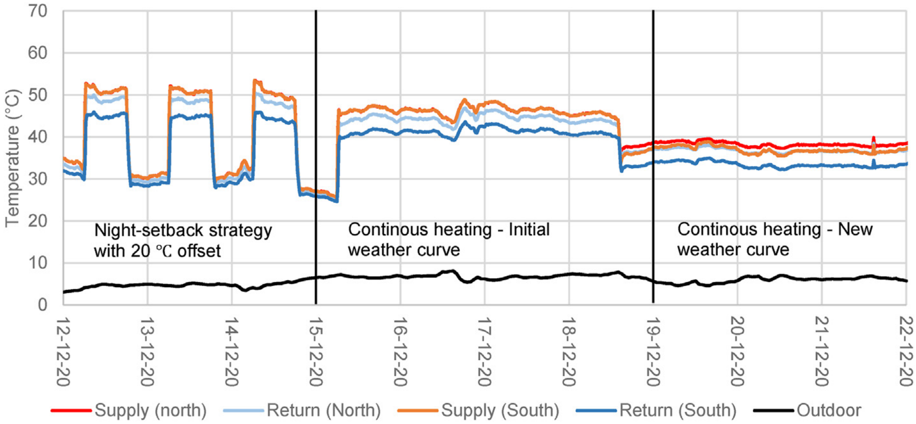

Fig. 10. The space heating systems' supply and return temperature recorded by the BMS system under the test of the different control strategies. When the red curve is not visible, it is under the orange curve.

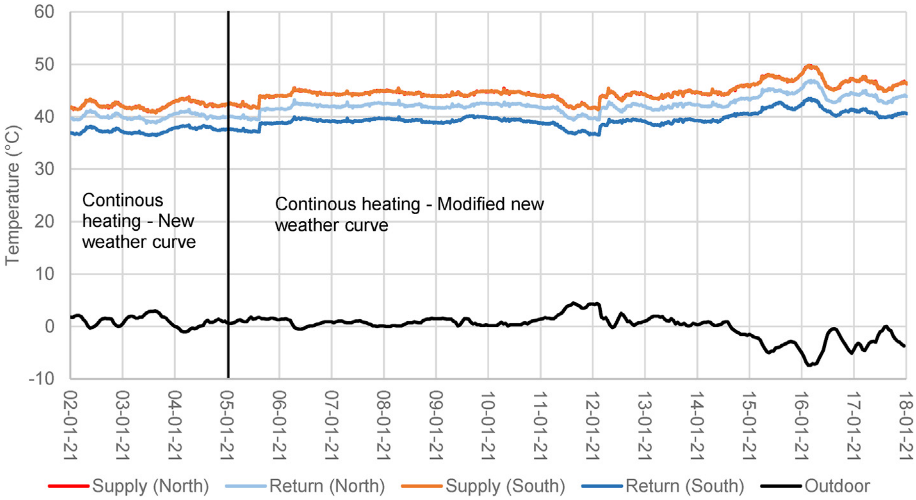

Fig. 11. The space heating systems' supply and return temperature recorded by the BMS system under the test of the modified new weather compensation curve by 2 °C. When the red curve is not visible, it is under the orange curve.

heating system operates under continuous heating according to the initial weather compensation curve presented in Fig. 4. The indoor temperatures resulting from IDA ICE in both offices are constantly at 22 °C. The indoor temperatures recorded from the temperature sensors in the actual rooms were 0.5 °C and 1 °C lower in the south and north office, respectively. This small difference could be explained due to the difference in internal gains between the actual operation of the building and the building simulations. In December of 2020, no occupants were present in the building, while typical internal gains were considered in the building simulations. As a result, the IDA ICE model resulted in similar indoor temperatures during the examined period under the same control strategy.

Table 4 presents the IDA ICE model validation results for April 2020. The heating use in the model was lower than the actual use because the model did not include the gable rooms in the representative section. The gable rooms have a higher heat loss than a typical office room in the middle of a building. The difference between the model height and the actual building height considering the suspended ceiling, which was not included in the IDA model, was also a contributing factor. From the difference between the measured and simulation results for April 2020, it can be concluded that the IDA ICE model is a good approximation of the actual building case.

Fig. 13 presents the annual energy use per heated floor area (kWh/m^2) for the different control strategies according to the IDA ICE model simulations. According to the results, the night setback control strategy resulted in energy use for heating of 60.4 kWh/m^2, which is a reduction of 11.8% compared to the continuous heating with the initial curve. Continuous heating under the new modified weather curve resulted in energy use for heating of 60.7 kWh/m^2, which is a reduction of 11.3% compared to the initial curve. Continuous heating under the minimum supply temperature resulted in energy use for heating of 58.9 kWh/m^2, which is a reduction of 14% compared to the initial curve.

In Table 5, the number of occupancy hours when the indoor temperature was below 22 °C and 21 °C is presented for the office room with north orientation on the 2nd floor of the module. According to the results, the modified new weather curve is sufficient to secure thermal comfort in the critical room.

5. Economic benefits from the low-temperature operation

Table 6 presents the economic benefits of using night setback and continuous heating with the new weather compensation curve, compared with continuous heating with the initial weather compensation curve. The use of night setback resulted in the highest energy savings, while continuous heating with the new weather compensation curve resulted in the lowest operating temperatures.

Table 4
IDA ICE model validation results during April of 2020.

Parameter	Measured value	Simulation result	Difference
Space heating use (kWh/m^2)	4.16	3.84	8%
Electricity (kWh/m^2)	1.13	1.10	3%

According to Table 6, continuous heating with a minimum supply temperature may result in higher cost reduction, taking into account the economic benefit from the motivation tariff for low-return temperature than a typical night setback strategy. The cost reduction due to the reduction of energy use is similar between the two strategies. Although, the significant reduction of the energy weighted return temperature under the new weather compensation curve resulted in a higher cost reduction than the night setback strategy.

6. Discussion

6.1. The results from the case study

The two different control strategies were tested in the specific office building case in Denmark. The building was renovated by improving the glazing elements and had a relatively low energy demand. The results indicate that low-temperature continuous heating can be an alternative to the commonly used night setback strategy in low-energy buildings like the specific building case, resulting in similar energy savings. The energy savings from night setback strategies might be higher for high-energy buildings than from continuous low-temperature heating. As a result, each building case has to be evaluated individually.

According to the aim of this study, the test of the different strategies was based on adjusting the existing old control system with no additional cost for replacing control components. The night setback control strategy tested was based on a typical control approach by reducing the supply temperature of the weather compensation control by 20 °C. More advanced night setback and reheating control strategies might have had a better performance. However, in many old buildings like the selected building case, there are limitations regarding the type of night setback implemented in the control system as part of very large and old BMS system.

The test of all strategies was performed during a period without occupants in the building and no additional internal gains. As a result, if the building was under the usual occupation schedule, the indoor temperatures recorded might be higher.

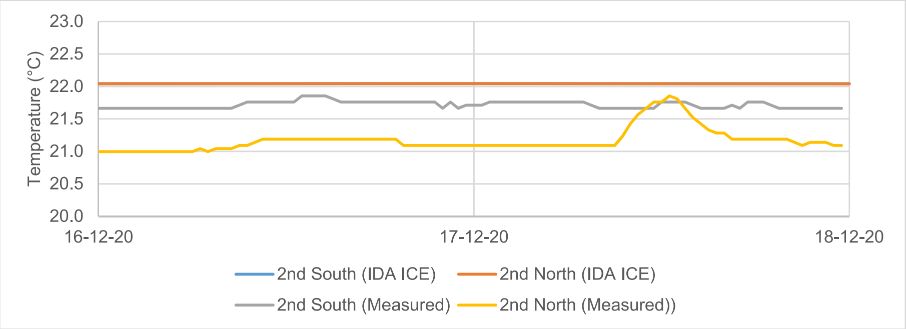

Fig. 12. The indoor temperature of a south and north office on the second floor according to the IDA ICE simulation results and actual measurements on the 16th and 17th of December of 2020 under continuous heating with the initial weather compensation curve.

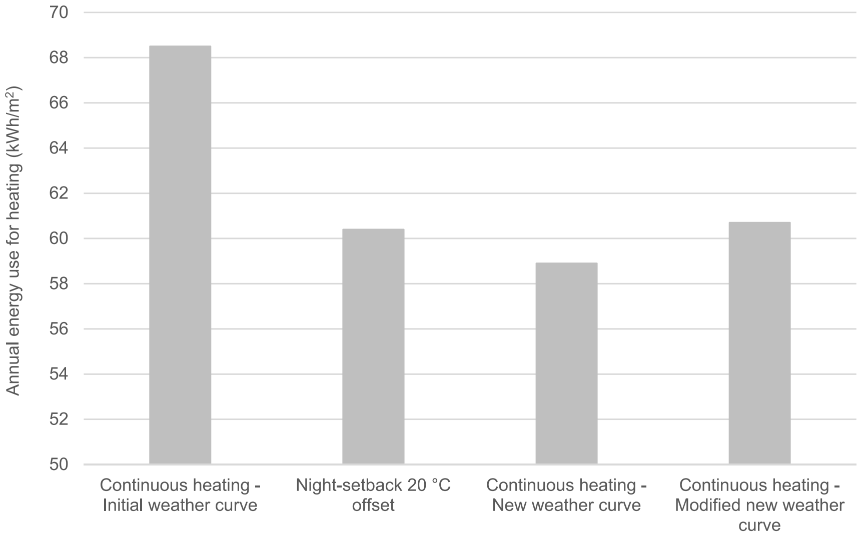

Fig. 13. Calculated annual energy use (kWh/m^2) for the different control according to the IDA ICE model simulations.

Table 5
The number of hours during the occupancy schedule where the indoor temperature is below 22 °C and 21 °C.

Control strategy	Number of hours below 22 °C	Number of hours below 21 °C
Continuous heating – Initial weather curve	0	0
Night-setback 20 °C offset	2	0
Continuous heating – New weather curve	528	0
Continuous heating – Modified new weather curve	48	0

Table 6
Comparison between night setback and continuous heating with the new weather curve, based on the cost savings due to the reduced energy use and the economic benefit due to the motivation tariff for low-return temperature.

	Energy savings (%)	Cost reduction due to energy savings (%)	Energy weighted average return temperature (°C)	Cost reduction due to motivation tariff (%)	Total cost reduction (%)
Continuous heating – Initial curve	–	–	55.5	–	–
Night-setback 20 °C offset	11.8	11.8	48.7	6.8	18.6
Continuous heating – New weather curve	14	14	41.9	13.6	27.6
Continuous heating – Modified new weather curve	11.3	11.3	43.7	11.8	23.1

The test of the night setback strategy showed acceptable indoor temperatures in most of the offices in the morning. The reason was that the initial weather compensation curve used resulted in a high supply temperature to reheat the building within a short period.

Fig. 9 shows the continuous heating control test results and the relative indoor temperature variation in different offices/rooms. In gable rooms of the building case (room 002 and 202), due to the higher heat losses and radiators of the same size as in the rest of the offices, the recorded indoor temperature in the first test was lower than typical offices in the middle of the building. This problem could be solved by replacing the existing heating elements with new ones. However, a simple solution with no extra cost was to increase the temperature of the weather compensation curve. For the continuous low-temperature heating, the supply temperature of the new weather compensation curve was increased by 2 °C. During the second test, the new supply temperature curve resulted in acceptable indoor temperatures also in the gable rooms. Hence, the supply temperature control of the heating system in buildings has to be adjusted, taking into account the critical rooms in the buildings. Rooms equipped with radiators with insufficient capacity can be found in both office and multi-family residential buildings and consequently, the supply temperature should be adjusted to secure an acceptable indoor temperature in these critical rooms.

Regarding the north meeting room on the ground floor (room 007), due to the misplaced temperature sensor of the thermostatic radiator valve, the setting of the valve was changed to “5″ to secure an acceptable indoor temperature. This solution cannot be a recommended solution. However, it was used only in this building case as a quick solution to compensate for the higher indoor temperature around the sensor that limited the radiator's heat output according to the actual heat demand of the room. As identified in this building case, misplaced temperature sensors are a general problem that can be found in any building. The TRV sensors should be mounted correctly.

The energy savings calculated by the dynamic simulations resulted mainly from the reduced heat losses from the pipes in the unheated basement. This problem identified in the specific building case is a common problem in many buildings with uninsulated long distribution pipes. The distribution heat losses depend on the supply temperature. In addition, a part of the energy savings was taking place in the offices due to the increased efficiency of the heating system at lower operating temperatures. As a result, the minimum supply temperature implemented results in the lowest distribution heat losses, as shown in Table 6.

The modified new weather curve resulted in supply temperature below 55 °C for design conditions. This is in line with the temperature requirements for LTDH. However, the energy weighted average return temperature of 43.7 °C was relatively higher than the requirements for LTDH. This temperature may be reduced further when the building and the heating system will be renovated in the future.

6.2. Relevance of the results in other buildings in different countries

The initial operation of the heating system was based on a high supply temperature to address complaints regarding poor thermal comfort. This is a common problem for both office and multi-family residential buildings connected to DH networks. The need for a high supply temperature for the heating system results in high operating temperatures in DH networks that result in high distribution heat losses. The use of low supply and return temperature results in lower distribution heat losses and enables the integration of renewable energy sources and central heat pumps into the DH network.

The common intermittent heating control strategy has been proved to secure energy savings in office buildings in different countries. It is also a significant problem for DH systems towards LTDH because the rapid reheating process in the morning creates unnecessary peak loads and hydraulic capacity problems in the networks.

During the reheating process, the high supply temperature results in a high return temperature to the DH network. Typically, high return temperatures reduce the temperature difference in the networks and create the hydraulic capacity problem. A lower return temperature would allow DH operators to reduce the supply temperature. The elimination of the reheating period would also minimise the peak loads and the necessity to turn up the costly and highly polluting fossil-fuel peak boilers. As a result, using an alternative control strategy that may secure similar energy savings and result in a low-return temperature without peak loads is of high importance for DH systems worldwide.

This article investigated the continuous low-temperature control strategy as an alternative to the intermittent heating control strategy in an office building in Denmark that is part of a local DH system. The analysis focused on improving the operation of the heating system of the building case by securing a low-temperature operation. The low-temperature operation of heating systems in buildings enables the DH network's low-temperature operation [13]. According to the specific building case results, the continuous low-temperature control strategy resulted in similar energy savings to intermittent heating and secured a low supply and return temperature to the DH network. However, the energy savings obtained depend on the heat loss and the size of the distribution system of each specific building. Consequently, the continuous low-temperature control strategy is relevant to be investigated in any office building connected to the DH network.

Finally, implementing the motivation tariff for low-temperature operation in the specific building case showed an additional economic incentive for the end-users to secure a low-temperature operation of the heating system and consequently to the DH network. As a result, the motivation tariffs have a two-fold advantage and should be considered a viable solution across all of Europe [13]. First, they incentivise end-users to responsibly use their heating systems in exchange for a discount on their energy bills and make them part of the transition toward a sustainable energy system. In addition, they help reduce the operating temperatures in the networks and ensure an economic benefit for DH operators, as quantified and documented in the Danish local DH networks in the Viborg municipality [11].

6.3. Limitations of the case study

In the specific case of an old office building, the BMS system does not have all the control possibilities to investigate different intermittent heating strategies to optimise the energy savings. This might be a common problem in older buildings. As a result, the energy savings obtained under intermittent heating might be limited to the control system of the building. Consequently, the energy savings obtained by the easily applied constant low-temperature operation could be worth to be investigated.

Moreover, as stated in Refs. [20,21], the energy savings due to intermittent heating varies based on the heat loss of the specific building. Both intermittent heating and the continuous low-temperature operation resulted in similar energy savings in the specific building case. This might not be the case in other buildings with higher heat losses. In these building cases, intermittent heating might result in higher energy savings than continuous low-temperature operation.

The specific building case is part of a local DH network located in Denmark, where it is common to have motivation tariffs to promote the low-temperature operation of the heating systems in the Danish DH market. They secure an economic benefit for low supply and return temperatures in the substation. This economic incentive is not widely applied in different countries. Therefore, the proposed economic analysis under this article cannot be applied in other building cases in different countries without a similar motivation tariff structure.

7. Conclusions

This article aimed to compare a typical night setback strategy with low-temperature continuous heating in a specific building case of an office building in Denmark., with no additional cost for replacing the existing control components connected to a local DH network under a typical motivation tariff for low-temperature operation policy.

The test of the two control strategies during a period with no internal gains showed that sufficient thermal comfort could be secured in most offices. A lower temperature was recorded in the gable offices. For the low-temperature continuous heating strategy, a simple solution regarding the gable offices without additional cost was to increase the new weather compensation curve by 2 °C. This new modified weather compensation curve test showed a sufficient indoor temperature of approximately 21 °C in all rooms.

The new modified weather compensation curve resulted in supply temperatures below 55 °C for design conditions. An energy weighted average return temperature of 43.7 °C could be achieved, which was reduced by 12 °C compared to the initial operation.

The dynamic simulation results showed that both strategies yielded similar energy savings for heating of approximately 11%. Moreover, the lower energy weighted average return temperature calculated under the two strategies resulted in additional cost savings due to motivation tariff. Under low-temperature continuous heating, the return temperature was relatively lower than the night setback strategy. The cost savings under low-temperature continuous heating and night setback strategy were estimated to be 23.1% and 18.6%, respectively.

As a result, continuous low-temperature heating can secure the required comfort and achieve the most significant cost reduction for heating in the specific building case because of the motivation tariff for low return temperatures.

This article's results refer only to the specific office building in Denmark and DH systems with motivation tariffs for low-temperature operation. Although, the use of continuous low-temperature heating in buildings may result in energy savings similar to intermittent heating control strategies depending on the heat demand profile of each specific building. In addition, the implementation of motivation tariff policies for low-temperature operation in DH networks in different countries towards LTDH may provide additional economic incentives to be considered besides energy savings. Therefore, it is interesting to investigate the use of continuous low-temperature heating in buildings connected to DH and quantify the energy and cost savings.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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